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Effects of surface passivation on breakdown of AlGaN/GaN high-electron-mobility transistors

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The effect of Si_3N_4 surface passivation on breakdown of AlGaN/GaN high-electron-mobility transistors was studied in detail by investigating dependences of the off-state breakdown voltage on temperature and gate reverse current, and by measuring electroluminescence distribution. Impact ionization in the channel which was triggered by the gate reverse current was responsible for the off-state breakdown. Surface passivation by Si_3N_4 film was effective to improve the off-state breakdown voltage. This has been explained by a change in the potential distribution due to suppression of electron trapping at the surface states, based on results of electroluminescence measurements. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1687983]

AlGaN/GaN high-electron-mobility transistors (HEMTs) have received much attention for their ability to operate at high-power levels because of a high breakdown field in the wide band gap semiconductor.[1,2] The off-state breakdown voltage (BV_{off}) is one of the most important parameters for the device because it determines a maximum output power, $P_{\max} \sim I_{\max} \times BV_{\mathrm{off}}/8$ for class A operation. Here, $I_{\max}$ is the maximum drain current. Green *et al.* have reported that breakdown voltage of AlGaN/GaN HEMTs was improved by using a Si_3N_4 surface passivation layer, and consequently the mechanism of breakdown was considered to be related to the surface.[3]

Recently, we have also observed an increase in BV_{off} by Si_3N_4 surface passivation. However, in our previous work, it has been shown that the mechanism of breakdown in devices without surface passivation is related not to the surface but to the impact ionization in the channel.[4] The effect of surface passivation on breakdown has not been sufficiently understood.

In this letter, we have studied the effect of surface passivation in detail, based on the temperature dependence and gate reverse-current dependence of BV_{off} and electroluminescence (EL) distribution.

AlGaN/GaN HEMTs used in this work were fabricated on an AlGaN/GaN heterostructure grown by metalorganic chemical vapor deposition on a (0001) sapphire substrate.[5] The epitaxial layer structure is i-AlGaN (5 nm)/n-AlGaN (10 nm,4×10^{18} cm^{-3})/i-AlGaN (5 nm)/i-GaN (3 μm)/ i-AlN (40 nm).[5] The AlN mole fraction of the AlGaN layers is 0.3. A Si_3N_4 passivation layer with a thickness of 100 nm was deposited by using the electron-cyclotron-resonance sputtering method. The gate length (L_g) was 1.5 μm. The gate-source and gate-drain spacings were 1.5 and 2 μm, respectively. The gate width was 20 μm. The threshold voltage was about -3 V. The maximum drain current and transconductance were 425 mA/mm and 105 mS/mm, respectively, for a 1.5 μm gate device.

The temperature dependence measurement is useful in understanding the breakdown mechanism.[4,6,7] When the breakdown was dominated by impact ionization, the temperature dependence had a positive coefficient. This is because the electron mean free path that is limited by phonon scattering is shorter in a higher temperature, and then higher electric field is required to gain energy necessary for the impact ionization. In the case of surface breakdown, on the other hand, the temperature dependence has a negative coefficient because the main mechanism of the transport through surface states is the hopping conduction, which is significant at high temperature. Figure 1 shows the temperature dependences of BV_{off} for the devices with (closed circle) and without (open circle) surface passivation. Here, the L_g was 1.5 μm and the drain-source voltage (V_{GS}) was -5 V. Here, BV_{off} was defined as the drain-gate voltage (V_{DG}) at which the increase in drain current (I_{D}) was 0.05 mA/mm when the I_{D} drain-source voltage (V_{DS}) characteristics were measured. BV_{off} increased by $\sim$35% at 300 K by the Si_3N_4 surface passivation. BV_{off} of both devices showed positive temperature coefficients, indicating that the mechanism of the off-state breakdown was impact ionization in the channel[4,6] rather than surface breakdown.[7]

Figure 2 shows BV_{off} of various devices with different L_g from 1.5 to 10 μm as a function of the reverse gate

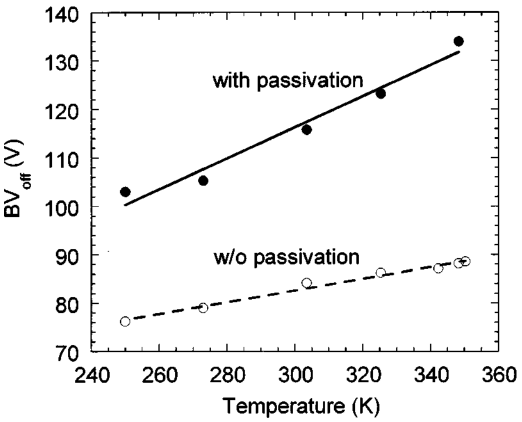

FIG. 1. Temperature dependence of off-state breakdown voltage.

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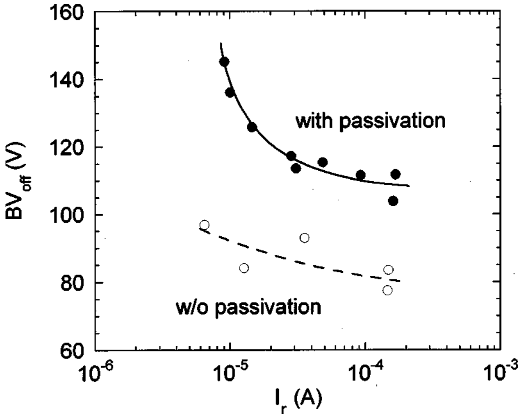

FIG. 2. Off-state breakdown voltage as a function of gate reverse current.

current (I_r). Here, in the present devices, I_r varied in proportion to L_g, which indicates that contribution of surface leakage current was small and that the dominant component of I_r was due to electron injected from the gate electrode into the channel. Closed and open circles are BV_{off}s of devices with and without surface passivation, respectively. BV_{off}s decreased with increase in I_r. This suggests that the impact ionization was caused by electrons injected from the gate electrode. More detailed discussion about the relation between I_r and BV_{off} was reported in Ref. 4. The difference in the dependence of BV_{off} on I_r between devices with and without the surface passivation was probably attributed to the difference of the potential distribution between the gate and drain. High field between the drain and gate was relaxed by the surface passivation.

From the above results, a mechanism of the off-state breakdown can be explained by impact ionization in the channel which was triggered by electrons tunneling from the gate to the channel, regardless of the existence of surface passivation. It is worth noting that BV_{off} increased by the surface passivation, whereas the breakdown mechanism in present devices was related not to surface breakdown but to impact ionization in the channel.

In order to study the reason why BV_{off} increased by the surface passivation, EL distribution was measured using a microscope and a charge-coupled-device camera. Details of the measurement setup and luminescence mechanism were described in Ref. 8. Figure 3 shows EL distributions in devices (a) without and (b) with surface passivation. Here, L_g of two devices was 1.5 μm. The devices were biased at (a) $V_{\mathrm{DS}}=70$ V and (b) $V_{\mathrm{DS}}=100$ V, respectively. In order to obtain detectable luminescence intensity, the V_{GS} was set to be slightly above threshold voltage ($V_{\mathrm{GS}}=-2$ V). In the case of the device without surface passivation, EL was observed at the drain edge, suggesting that the high-field region was formed at the drain edge. This is in contrast to standard III-V HEMTs where a high-field region is formed at the gate edge.

The high-field formation at the drain edge can be explained by taking into account "virtual gate."[9,10] The schematic drawing of charge distribution and potential profile between the gate and drain electrodes is shown in Fig. 4(a). The virtual gate which has almost the same potential as the gate electrode is formed between the gate and drain electrodes by electrons injected from the gate to surface states. Then, a large potential drop occurs at the drain edge.

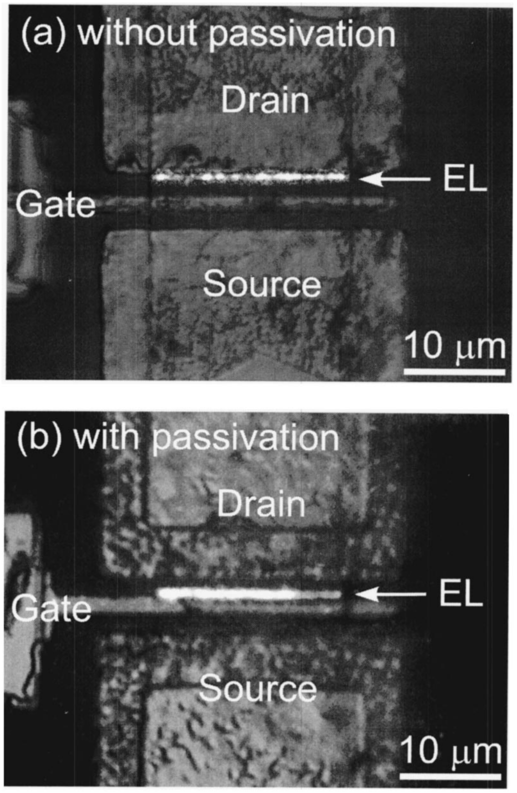

FIG. 3. Electroluminescence distribution in AlGaN/GaN HEMTs (a) without and (b) with surface passivation.

In the device with surface passivation, on the other hand, EL was observed at the gate edge of the drain side as shown in Fig. 3(b). This indicates that the increase in BV_{off} by the

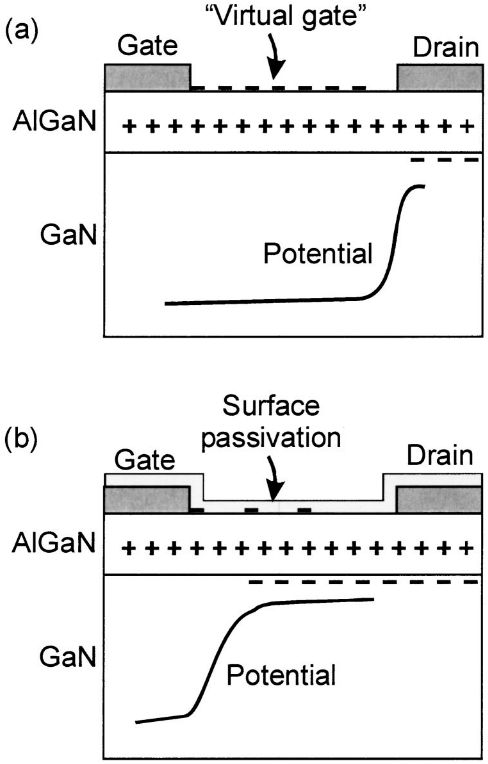

FIG. 4. Schematics of charge distribution and potential profile between gate and drain electrodes; (a) without and (b) with surface passivation.

surface passivation was due to change in potential distribution between the gate and drain electrodes. By introducing the Si_3N_4 surface passivation film, electron trapping at surface states was probably suppressed, and the high field at the drain edge was relaxed. Then, a potential drop occurred at the gate edge, and moderate field strength was formed as shown in Fig. 4(b).

The ungated drain current was not changed by the Si_3N_4 passivation. This suggests that the surface states with positive charge reported by Ibbetson *et al.*[11] were not eliminated if charge neutrality condition is considered. This can be understood if we take into account that the positive surface states originate from N vacancies of the AlGaN layer.[12] A possible explanation of the suppression of electron trapping is as follows. In addition to the positive surface states, there might exist another type of surface state which is neutral when it is empty of electrons. Even though the positive surface states were not eliminated, the neutral surface states were decreased by the passivation. If electron injection from the gate and capture by the surface states were suppressed, high field at the drain edge would be relaxed. Quantitative discussion will be the subject of further investigation.

In conclusion, the mechanism of off-state breakdown and the effect of surface passivation on the breakdown in AlGaN/GaN HEMTs have been investigated by measuring dependence of BV_{off} on temperature and gate-reverse current and electroluminescence distributions. Impact ionization in the channel, which was triggered by electrons injected from the gate to the channel at a large gate-reverse bias, was responsible for the breakdown. BV_{off} increased by Si_3N_4 surface passivation by $\sim 35\%$ at room temperature. The behavior was explained, based on the EL measurement, by redistribution of electric field due to change in charge of surface state. In order to further improve BV_{off}, it is important to suppress gate reverse current.

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